The Holocene, 5,2 (1995) pp. 229–237

The 'segment length curse' in long tree-ring chronology development for palaeoclimatic studies

Edward R. Cook[1], Keith R. Briffa[2], David M. Meko[3], Donald A. Graybill[3] and Gary Funkhouser[3]

([1]Tree-Ring Laboratory, Lamont-Doherty Earth Observatory, Palisades, New York 10964, USA; [2]Climatic Research Unit, University of East Anglia, Norwich NR4 7TJ, UK; [3]Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona 85721, USA)

Received 15 December 1994; revised manuscript accepted 2 January 1995

A HOLOCENE FORUM ARTICLE

Abstract: The problem of constructing millennia-long tree-ring chronologies from overlapping segments of cross-dated ring-width series is reviewed, with an emphasis on preserving very low-frequency signals potentially due to climate. In so doing, a fundamental statistical problem coined the 'segment length curse' is introduced. This 'curse' is related to the fact that the maximum wavelength of recoverable climatic information is ordinarily related to the lengths of the individual tree-ring series used to construct the millennia-long chronology. Simple experiments with sine waves are used to illustrate this fact. This is followed by more realistic experiments using a long bristlecone pine series that is randomly cut into a number of 1000-, 500- and 200-year segments and standardized using three very conservative methods. When compared against the original, uncut series, the resulting 'chronologies' show the effects of segment length even when the most conservative and noncommittal method of tree-ring standardization is applied (i.e., a horizontal line through the mean). Alternative schemes of chronology development are described that seek to exorcise the segment length curse. While they show some promise, none is universal in its applicability and this problem still remains largely unsolved.

Key words: Tree-rings, dendroclimatology, chronology standardization, 'segment length curse', palaeoclimatology

Introduction

The development of millennia-long tree-ring chronologies often involves the use of wood specimens collected from both living trees and subfossil logs or remnants of a given species in a region. The overlapping tree-ring series from these specimens are linked together through crossdating, and this process enables the chronology to be extended back in time, in some cases several thousand years (e.g., Ferguson and Graybill, 1983; Pilcher *et al.*, 1984). Given that strong crossdating exists between the overlapping tree-ring series, the process of chronology development by a trained dendrochronologist is somewhat mechanical and relatively straightforward if the primary purpose of the long chronology is for tree-ring dating alone. With this purpose in mind, Ferguson (1969) applied a 7-year high-pass filter to his 7104-year bristlecone pine chronology prior to its publication, with the realization that low-frequency growth fluctuations due to climate had been removed. However, once the interest in millennia-long chronologies shifts from dating to climatic interpretation (e.g., LaMarche 1974), the development and interpretation of such records is no longer so straightforward and, indeed, still remains highly problematical.

Here we describe and illustrate in some detail one outstanding problem in the field of long tree-ring chronology development, which we call the 'segment length curse'. To understand the basis of this statistical problem, consider the hypothetical situation in which a deposit of subfossil wood has been found that spans the entire Holocene. Some of the subfossil ring-width segments will come from wood thousands of years older than other pieces and, therefore, from distinctly different periods of climate. For example, wood from the Hypsithermal (*c.* 7000–9000 years BP) might have grown in a distinctly warmer climate than wood grown in more recent times. This implies that a centuries-long trend in mean ring-width from our hypothetical deposit of subfossil wood could

© Edward Arnold 1995

Downloaded from http://hol.sagepub.com by guest on May 20, 2008
© 1995 SAGE Publications. All rights reserved. Not for commercial use or unauthorized distribution.

be driven by climate as well as by ageing or changes in stand structure and site conditions, a trend that could exceed the length of any of the individual segments and even the maximum lifespans of the tree species being exploited. The usual methods of tree-ring standardization (described below) do not take into account this possibility because they were largely developed for processing ring-width series from stands of comparatively young (i.e., centuries-old) living trees. In this situation, ring-width growth trends are usually assumed to be generated by nonclimatic processes related to changing tree size and age and by stand dynamics. For this reason, such trends are modelled as nonclimatic noise and removed using some kind of curve fitting or filtering method (Cook, 1987; Briffa *et al.*, 1987; Cook *et al.*, 1990). Thus, traditional tree-ring standardization methods would seem to place a fundamental limit on the resolvability of very low-frequency climatic fluctuations from tree-rings when climate changes more slowly than the typical life span of the trees being studied.

Next, we will describe in more detail the relationship between the segment length curse and traditional tree-ring standardization used in creating tree-ring chronologies. This will be followed by a review of some methods that have attempted to exorcize this curse from long tree-ring chronologies.

Tree-ring standardization and resolvability

Consider an idealized series of radial increment measurements R_t that is n years in length, collected from a tree growing in a disturbance-free, open-canopy forest. While somewhat unusual worldwide, such forests can be found in semi-arid regions, typically at the upper and lower elevational limits of tree growth. Now based on the allometry of tree growth and its effect on radial increment (and ignoring the early juvenile growth increase often found in such trees), it is usually the case that this 'raw' ring-width series will exhibit a decreasing trend with increasing age out to some positive, asymptotic limit k for over-mature trees. A useful model for this age-related trend in ring-width series is the modified negative exponential curve (Fritts *et al.*, 1969) of the form:

$$G_t = ae^{-bt} + k \tag{1}$$

where a is the intercept, b is the slope, k is the aforementioned asymptote, and t is time in years. Since the observed trend in ring widths is generally believed to be mostly biological in origin (as far as it is related to tree age and size), the usual practice is to remove it from the tree rings by fitting some sort of smooth growth curve to the ring-widths, like the modified negative exponential curve. The fitted annual growth curve can be thought of as a series of expected values of growth that would have occurred anyway in the absence of higher-frequency influences on ring width due to climate variability and other exogenous variables. That is:

$$\mathrm{E}[R_t] = G_t \tag{2}$$

Taking the ratio of the actual-to-expected ring-width for each year yields a set of dimensionless tree-ring 'indices' with a defined mean of 1.0 and a roughly homogeneous variance, viz:

$$I_t = R_t/G_t \tag{3}$$

where R_t and G_t are the actual and expected ring-widths and I_t is the resultant tree-ring index, all for years $t = 1,n$. An alternative way of expressing this relationship, and one that is much more informative, is due to Monserud (1986) who showed that if the relationship between R_t and G_t is expressed in the form of a simple regression equation, viz.:

$$R_t = G_t + E_t \tag{4}$$

then:

$$I_t = 1.0 + E_t/G_t \tag{5}$$

In this form, tree-ring indices are seen to be a series of residuals from G_t scaled by $1/G_t$ to make them homoscedastic, and the long-term mean is explicitly derived. It is also apparent that the $1/G_t$ transformation is intimately related to the goodness-of-fit of G_t. This follows by noting that, if the mean of R_t is used as an estimate of G_t, then the E_t will be scaled by a constant, which results in no variance stabilization at all.

This process of detrending and transforming the tree-ring variables to dimensionless indices is known as 'standardization' because it tends to equalize the growth variations of trees over time regardless of age or size (Fritts, 1976). Most importantly, the transformation to indices allows for averaging the cross-dated series from m individual trees into a mean-value function that more reliably reflects the high-frequency variations in growth presumably not related to the biological growth trends that were removed.

Up to this point, the standardization procedure just described is valid for constructing any mean tree-ring chronology, whether from living trees, subfossil wood, or an overlapping combination of both. The actual kind of expected growth curve used to standardize the ring-width series might change depending on the characteristics of the data (Cook, 1987; Cook *et al.*, 1990), but the mechanics of standardization will remain the same. However, for simplicity we will continue to use hypothetical tree-ring data that only require simple, monotonic growth curves to model the biological growth trend. Now, given the development of a mean-value function of standardized tree-ring indices from m trees, how do the lengths of the individual trees affect the amount of recoverable climatic information in the overall record?

If only living trees of comparable age are used to generate the mean index series, the maximum wavelength of recoverable climatic information will approach the total length of the mean tree-ring chronology being analysed. In the frequency domain, this information will be distributed in various ways from the highest (or Nyquist) frequency of *1/2* cycles per year (cpy) for annual data to the lowest frequency of *1/n* cpy. The latter is referred to as the 'fundamental frequency' (Jenkins and Watts, 1968) and is the lowest-frequency component in a time series that can be theoretically resolved from the long-term mean or trend (i.e., that which was removed by standardization). In the time domain, this is equivalent to a sine wave with a wavelength of n years. So for a 300-year chronology, it is possible in principle to identify a climatic fluctuation or cycle of that duration in the data (in fact, the realistic frequency limit is probably more like *3/n*, or 100 years in this case). Granger (1966) used this theoretical limit in developing a model for the typical shape of an economic variable, one that also typically contains trend. In this model, he introduced the concept of 'trend in mean', which refers to all variance in a time series at wavelengths longer than the length of the series. Now suppose that the characteristic wavelength of that information is N years, where $N > n$. Then, given no prior

Downloaded from http://hol.sagepub.com by guest on May 20, 2008
© 1995 SAGE Publications. All rights reserved. Not for commercial use or unauthorized distribution.

information about the structure of this variance, Granger (1966) proposed that such information be lumped into the overall estimate of the time series 'trend in mean'. This means that climatic fluctuations or cycles that occur at wavelengths longer than the length of the tree-ring series will not be found in the standardized chronology because they have been removed as part of the expected, biologically based 'trend in mean'.

The above picture was simplified by assuming that all m series in the mean-value function were nearly equal in length and covered the same time period. However, if series length in the ensemble varies greatly due to widely different tree ages, the recoverable low-frequency climatic variance will almost certainly be degraded even though the overall mean series length remains the same. This follows by noting that the 'trend in mean', which is removed by standardization, is tied directly to the individual series length. Therefore, the shorter series in the ensemble will have lost some of the low-frequency information that would otherwise be preserved in the longer series.

Given that the resolvability limit is related to n, might it not be possible to extend that limit simply by increasing the length of the overall mean tree-ring chronology? The answer to this question is a qualified 'yes', depending on how it is done. For example, if older trees (i.e., those with more annual rings) are sampled and added to the ensemble, the resolvability limit will be extended in direct proportion to the increased length of the new mean chronology. However, if the series is only extended by using overlapping tree-ring series from subfossil wood, then the picture is not so clear. Consider for the moment the case where we have three crossdated 500-year tree-ring segments that overlap in time by 250 years, such that segment 1 covers years 1–500, segment 2 covers years 251–750 and segment 3 covers years 501–1000. After standardization to remove growth trends, the resulting mean chronology has a total length of 1000 years, but the frequency resolvability limit is not 1/1000 years as the overall series length would suggest. At best it is 1/500 years because each segment length defines the maximum wavelength that can be differentiated from the trend. Extending this example back 8000 years with 500-year overlapping segments does not change the outcome. We are still locked into a maximum frequency resolution of 1/500 years, or so it would seem. This is the essence of the segment length curse.

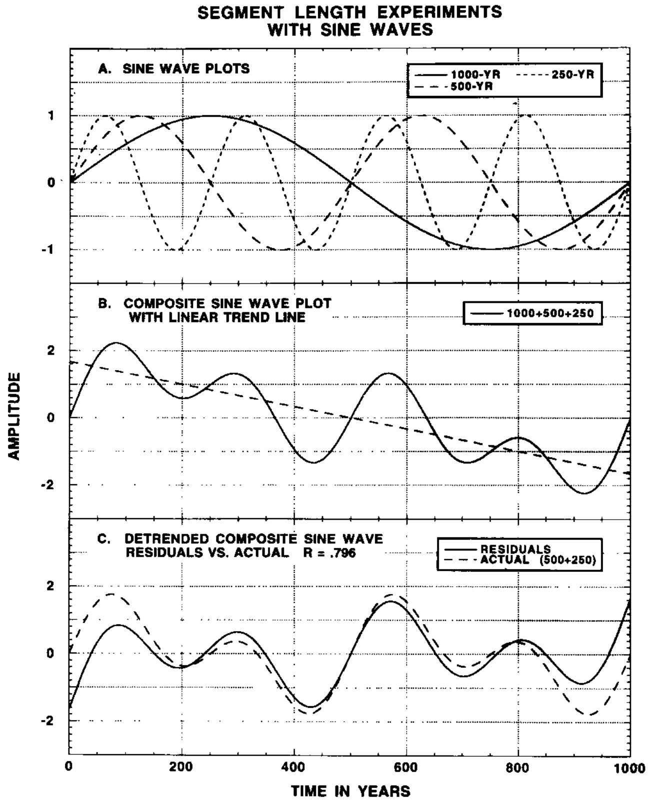

Figure 1 Segment length experiments with sine waves. (a) The 1st, 2nd and 4th harmonics of a 1000-year sine wave are used to illustrate aspects of the segment length curse. These three terms are considered to be theoretical climate signals in noise-free tree-ring data. (b) The composite plot of the three harmonics shown in (a). The linear trend line is fitted by simple linear regression and is meant to mimic the removal of biological growth trend in a raw ring-width series assuming no other information about the origin of the observed trend. (c) The composite sine wave residuals after removing the trend shown in (b). For comparison, the composite of the 500- and 250-year harmonics is overlaid with the residuals. As indicated by the correlation, these represent most of the signal left in the residuals after detrending, with the 1000-year harmonic being effectively eliminated as biological growth trend.

An illustrative example

A rather simplistic, yet instructive, example of these concepts and problems is illustrated in Figures 1 and 2. Figure 1a shows three pure sine waves of equal amplitude (a = 1.0) with periods of 1000, 500 and 250 years, each with an initial phase of zero. The combined series shown in Figure 1b therefore has the form:

$$Y = sin\,2\pi(\frac{1}{1000}) + sin\,2\pi(\frac{2}{1000}) + sin\,2\pi(\frac{4}{1000}) \quad (6)$$

These represent the 1st, 2nd and 4th harmonics of a 1000-year time series, with the 1st harmonic being the fundamental one. In this example, we will assume the combined series in Figure 1b represents the overall low-frequency climatic signal in a raw (i.e., unstandardized) tree-ring series. Due to the orthogonality of trigonometric functions, each harmonic has a correlation of 0.577 with the sum, i.e., each explains 1/3 of the total variance. Note the negative trend in the signal that is fitted by a linear regression curve. The trend is primarily due to the 1000-year harmonic. While a change in this harmonic's initial phase would alter the overall trend or even reverse it if the initial phase was shifted 180°, there is no *a priori* reason to modify it in any particular way.

Barring any prior information about the potential climatic significance of this trend, it is possible, or even likely, that it would be removed by standardization in the belief that it was principally biological in origin. Given this assumption, we removed the fitted linear trend and, in so doing, most of the 1000-year variance. In fact, the correlation between the 1000-year harmonic and the residuals from the linear trend line is only 0.059, much smaller than the expectation of 0.577 based on the original series in Figure 1b. The residuals from the curve are compared to a composite of the 500- and 250-year harmonics alone in Figure 1c. The correlation between the residuals and this reduced true signal is 0.796, a result that is consistent with expectation (0.816). The correlations of the individual 500- and 250-year harmonics with the residuals (0.439 and 0.688 respectively) are still reasonably close to expectation (0.707), although there is also clear degradation in the fidelity of the 500-year signal. However, the inadvertent loss of the 1000-year signal indicates that preserving signal strength at the theoretical resolution limit of

Downloaded from http://hol.sagepub.com by guest on May 20, 2008
© 1995 SAGE Publications. All rights reserved. Not for commercial use or unauthorized distribution.

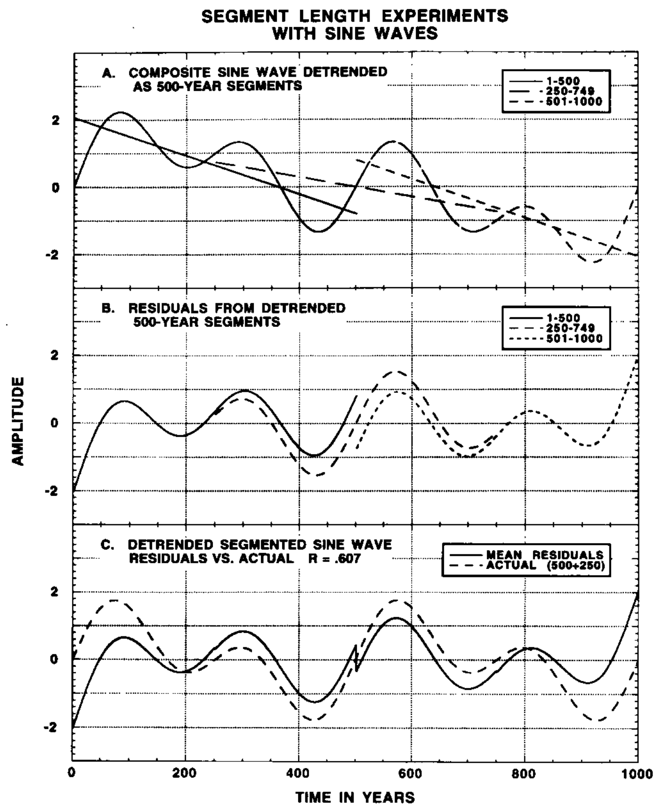

Figure 2 Further segment length experiments with sine waves. (a) The 3-harmonic composite from Figure 1b segmented and detrended as three overlapping 500-year trend lines. This process mimicks the detrending of overlapping raw ring-width series prior to their incorporation into a mean chronology. (b) The residuals produced by detrending the 3-harmonic composite as a series of three overlapping 500-year segments. Note the discontinuities in the central portion of the plots due to this process, which degrades the quality of the retained signals. (c) The composite sine wave residuals after removing the trends shown in (a). For comparison, the composite of the 500- and 250-year harmonics is overlaid with the residuals. As indicated by the correlation, there has been a clear degradation of the retained 500- and 250-year signals compared to that shown in Figure 1c.

$1/n$ may be difficult to achieve in practice if any kind of detrending is used. This result clearly illustrates the difficulty in trying to preserve variance at wavelengths longer than the series length when any kind of detrending is used.

Figure 2a expands the previous example by considering the case where three overlapping 500-year segments, each containing portions of the same 3-harmonic composite signal, are individually detrended. The composite signal is the same as that used previously (see Figure 1b) and the three trend lines shown cover the segment intervals. The slopes and intercepts differ noticeably even though they ought to be identical in theory. The result of these differences is revealed in Figure 2b, which shows the three overlapping sets of residuals. In the centre portion, there are some obvious offsets and biases that translate into a further loss of signal fidelity, as suggested in the previous section. The mean of these three 'standardized' series was compared to the composite of the 500- and 250-year harmonics. This comparison, shown in Figure 2c, reveals the loss of fidelity due to standardizing the three 500-year overlapping segments, as opposed to standardizing the full 1000-year record. As before, the 1000-year signal has been effectively removed so the comparison only involves the 500- and 250-year harmonics in the expected signal. The correlation between the expected signal and that obtained from the overlapping residuals is 0.607 as opposed to 0.796 in the previous test case. So, the strength of the true signal has been reduced by approximately 57% in the mean residual series. In terms of specific harmonics, the correlation between this record and the true 500-year harmonic declined from 0.439 in the previous case to only 0.239 here. In contrast, the correlation between the recovered and expected 250-year harmonic only declined from 0.688 and 0.620. The greatest loss of fidelity is in the 500-year harmonic, which is again consistent with expectation.

These simplistic examples have produced results that are very consistent with what would be expected from theory. Given that the theory is rather general in its specification, these examples can be regarded as realistic reflections of the segment length curse. In the next section, a more realistic example will be given.

A more realistic example

The examples provided above suffer from an element of abstractness because no tree-ring series behaves in such a clean trigonometric fashion. In this example, we use a 2757-year-long ring-width series from a bristlecone pine (*Pinus longevea*) growing in the White Mountains of California to illustrate in a more realistic fashion the operational existence of the segment length curse.

Figure 3a shows this series (I.D. 990549), which we converted to tree-ring index form by removing the long-term mean. While exhibiting considerable high-frequency variation, it also possesses strong low-frequency fluctuations at wavelengths longer than 200 years, which are emphasized in the filtered series (Figure 3b). This series will represent our expected signal due to climate. We do not claim that the observed changes in growth are, in fact, all climatic in origin. However, given the simple geometry of strip-bark radial growth in overmature bristlecone pines and the semi-arid, open-canopy nature of the Methuselah Walk site of this tree, we do not have *a priori* reasons to expect that the long-term growth fluctuations are strongly influenced by biological, nonclimatic effects either.

We have chosen three different segment lengths in this experiment: 1000, 500 and 200 years. The 1000- and 500-year lengths are in the range of the tree-ring series used to construct millennia-long bristlecone pine chronologies (Ferguson, 1969; LaMarche, 1974; Ferguson and Graybill, 1983), while the 200-year length is more typical of series used to construct the long European oak chronology (Pilcher *et al.*, 1984).

Each segment length test was performed as follows. For each segment length (NL), the original series in Figure 3a was broken up into a number of segments (NS) whose starting years were selected by a uniform random number generator. If a starting year for a segment was selected such that its full length would run off the recent end of the original series, the starting year was reflected back to cover the last NL years of the record. While somewhat artificial, this procedure guaranteed that all NS segments were equal in length. In addition, one segment was prescribed to have a starting year equal to that of the original series and another segment was prescribed to cover the last NL years of the original series. This guaranteed that the resulting mean chronology based on NS segments would have the same length as the original series. The number of segments used in each segment length experiment was chosen to produce reasonably equivalent sample sizes over time between experiments. This proved most difficult for the 1000-year case because it is a large fraction of

Downloaded from http://hol.sagepub.com by guest on May 20, 2008
© 1995 SAGE Publications. All rights reserved. Not for commercial use or unauthorized distribution.

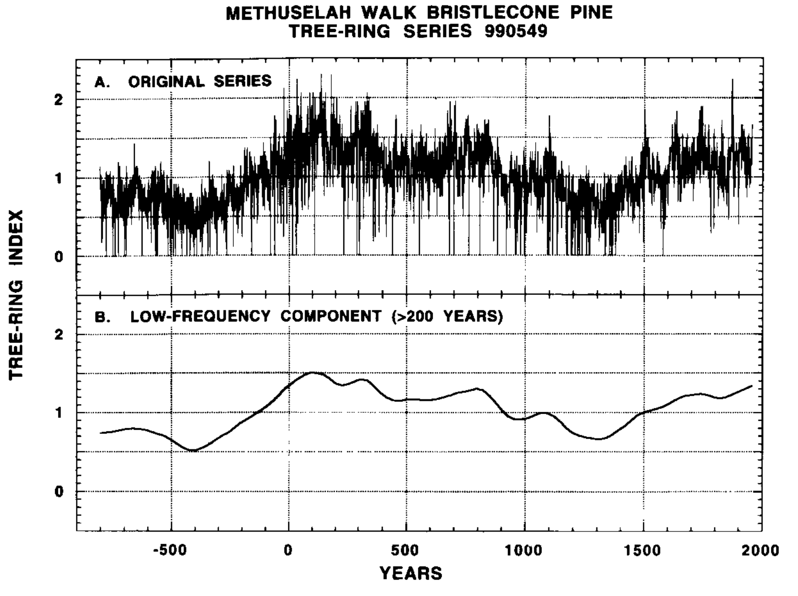

Figure 3 The long bristlecone pine series used in the segment length experiments. The series has been transformed from ring widths to dimensionless tree-ring indices for comparative purposes by standardizing it using the long-term mean. This series was kindly provided by Dr Donald Graybill and Gary Funkhouser, Laboratory of Tree-Ring Research, University of Arizona, Tucson.

the 2757 years in the original series. However, the results presented here are not markedly sensitive to the temporal distribution of sample size.

After the NS segments were selected for a given segment length, each segment was independently standardized using a very conservative detrending method. Three such methods were investigated here. The first method is simply based on removing from each segment its arithmetic mean, $\bar{x}$. Thus, this detrending method produces a growth curve of the form:

$$G_t = \bar{x} \tag{7}$$

for all years $t = 1,NL$. This method is the most conservative of those investigated here because it assumes the least amount of prior information regarding the expected form of the nonclimatic growth trend. All it assumes is that differences in long-term mean radial growth between segments, or series for that matter, are likely to be nonclimatic in origin, due perhaps to microsite differences or temporal/spatial changes in site quality. The second method is based on fitting a linear least-squares growth curve to each segment of the form:

$$G_t = a + bt \tag{8}$$

but constraining its slope b to be negative or zero. The constraint $b < 0$ is based on the argument that the geometry of radial growth ought to produce an age trend with a negative slope or, if the asymptote k has been effectively reached, zero slope. In this case, a positive trend in radial growth would be regarded as potentially due to a climatic change that favoured tree growth, increasing temperatures being one such example (e.g. Briffa *et al.*, 1992; Cook *et al.*, 1992). However, the slope constraint does not allow for any differentiation between a negative growth trend due to age-size effects and that due to climatic deterioration. The third method of detrending tested here simply eliminates the constraint on the slope used in the second method and thus allows linear trends of any slope to be removed from the segments being standardized. In this case, any trend in the tree-ring series is assumed to have been generated by nonclimatic processes. Of the three, the third method follows most closely Granger's 'trend-in-mean' concept and should produce results that most clearly reflect the $1/n$ resolvability limit in the frequency domain.

Figure 4a–c shows the sample size distributions for the three segment lengths used here. They are based on 50, 100 and 250 randomly selected overlapping segments for the 1000-, 500- and 200-year experiments, respectively, with the resulting median sample sizes being 19, 19 and 18. One interesting, if unexpected, outcome of the sample size distributions is the degree of random variation over time, which is especially apparent in the 200-year experiment. Simply by chance, sample sizes can vary by a factor of 2 or more and exhibit an episodic appearance as if periods of differential

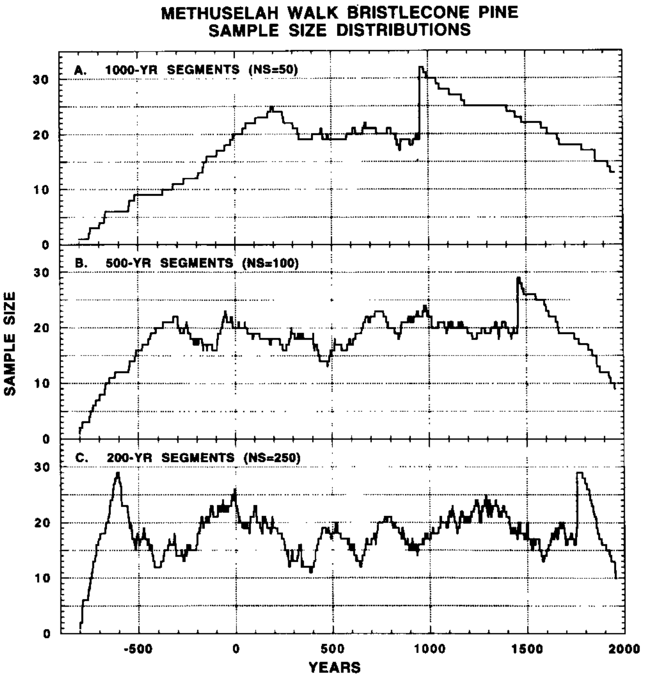

Figure 4 The sample size distributions for the three segment length experiments. See the text for a description of how these artificial sample size distributions were created. The median sample sizes are 19, 19 and 18 for the 1000-, 500- and 200-year segment length experiments, respectively.

Downloaded from http://hol.sagepub.com by guest on May 20, 2008
© 1995 SAGE Publications. All rights reserved. Not for commercial use or unauthorized distribution.

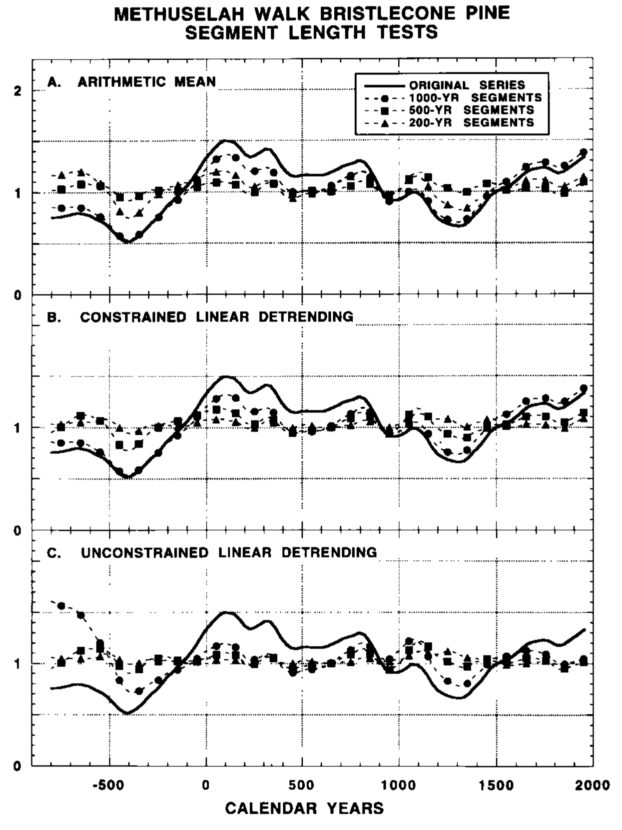

Figure 5 Segment length experiments using the long bristlecone pine series (Figure 3a). Only the low-frequency (>200-year) signal in each segment length chronology is compared with that from the original series (Figure 3b). (a–c) The resulting tree-ring chronologies developed from the three segment length experiments using different detrending methods. A comparison of these results with the original series indicates that most of the low-frequency variance is preserved using 1000-year segments and the most conservative method of detrending, the arithmetic mean. Conversely, almost all of the low-frequency signal is lost in using 200-year segments and unconstrained linear detrending.

recruitment and mortality had occurred in the past. This result should serve to caution against the overinterpretation of changing sample sizes over time (when these are generally based on low replication) as a proxy for past climatic/ environmental change. It also indicates that the significance of such observed changes might be tested using a random sampling procedure of the kind used here.

For each segment length, the NS segments were standardized using each of three detrending methods described above and averaged together to produce a mean index chronology of length 2757 years for comparison with the original series. Figure 5a–c shows the results of these experiments. Only the low-frequency (i.e., >200-year) component produced by each experiment is compared to that of the original (see Figure 3b) since this is where the largest effects of segment length should be found. Table 1 provides more quantitative information about the loss of signal amplitude and fidelity in both the unfiltered and low-pass filtered segment length series.

The 1000-year segment length experiments produced results that are very similar to the original series if the detrending was limited to either removal of the arithmetic mean or constrained linear detrending (Figure 5a–b). The generally good preservation of the low-frequency signal is probably due to the fact that the dominant low-frequency fluctuations in the original series do not noticeably exceed 1000 years. The similarity of these results is also due to the

Table 1 The standard deviations of the original series and those produced by the 1000-, 500- and 200-year segment length experiments using three different detrending methods. These results are given for both the unfiltered (Ampl) and the low-pass filtered series (Amp2) standard deviations. The correlation between the original and segment length series are also given for both the unfiltered (R1) and low-pass filtered (R2) versions. The standard deviations and correlations with the asterisks (*) were computed after deleting the first 250 values because of anomalously high values caused by detrending (see Figure 5c). If these values are left in, the standard deviations increase from 0.326 to 0.367 and from 0.127 to 0.182 for the unfiltered and filtered series, respectively. Conversely, the correlations decline from 0.872 to 0.717 and from 0.689 to 0.214, respectively.

	Ampl	Amp2	R1	R2
Original series	0.397	0.263	1.000	1.000
A. Arithmetic mean				
1000-year test	0.365	0.217	0.978	0.955
500-year test	0.329	0.110	0.840	0.603
200-year test	0.312	0.047	0.766	0.244
B. Constrained linear trend				
1000-year test	0.360	0.207	0.963	0.919
500-year test	0.322	0.089	0.839	0.652
200-year test	0.310	0.035	0.749	0.032
C. Unconstrained linear trend				
1000-year test	0.326*	0.127*	0.872*	0.689*
500-year test	0.318	0.064	0.746	0.091
200-year test	0.309	0.032	0.715	−0.372

fact that only 13 of the 50 1000-year segments had trends with negative slopes. Consequently, 74% of the segments only had the arithmetic mean removed when constrained linear detrending was used. Table 1 shows this high level of agreement between the arithmetic mean or constrained linear detrending, both in terms of amplitude (Ampl and Amp2) and correlation (R1 and R2) with the original series. However, there is still a greater loss of fidelity using constrained linear detrending (i.e., R2 drops from 0.955 to 0.919). In contrast, unconstrained linear detrending resulted in a substantial loss of signal amplitude and fidelity, especially in the lower frequencies. Taking into account a severe detrending artifact apparent in the first 250 years of the record (see Figure 5c), the low-frequency correlation is only 0.689. So, only 47% of the original low-frequency variance has been preserved due to the 1000-year segment length and unconstrained linear detrending.

The results of the shorter segment length experiments reveal much more serious losses of signal strength, as would be expected from theory. The arithmetic mean and constrained linear detrending experiments again produced somewhat similar results for the 500-year segment length experiment, only in this case the latter actually produced a slightly better low-frequency signal (R2 = 0.652) compared to the former (R2 = 0.603). However, the loss of low-frequency amplitude in either case is still quite high (falling from 0.263 to 0.110 and 0.089, respectively). In contrast, unconstrained linear detrending resulted in a catastrophic loss of both low-frequency signal fidelity (R2 = 0.091) and amplitude (falling from 0.263 to 0.064).

Finally, the 200-year segment length experiments show the continued degradation of the low-frequency signal that would be expected from the segment length curse. In this case, only the arithmetic mean has preserved any semblance of the original low-frequency signal (R2 = 0.244), although the amplitude is now only 18% of its original level (falling from 0.263 to 0.047). Constrained linear detrending now separates

Downloaded from http://hol.sagepub.com by guest on May 20, 2008
© 1995 SAGE Publications. All rights reserved. Not for commercial use or unauthorized distribution.

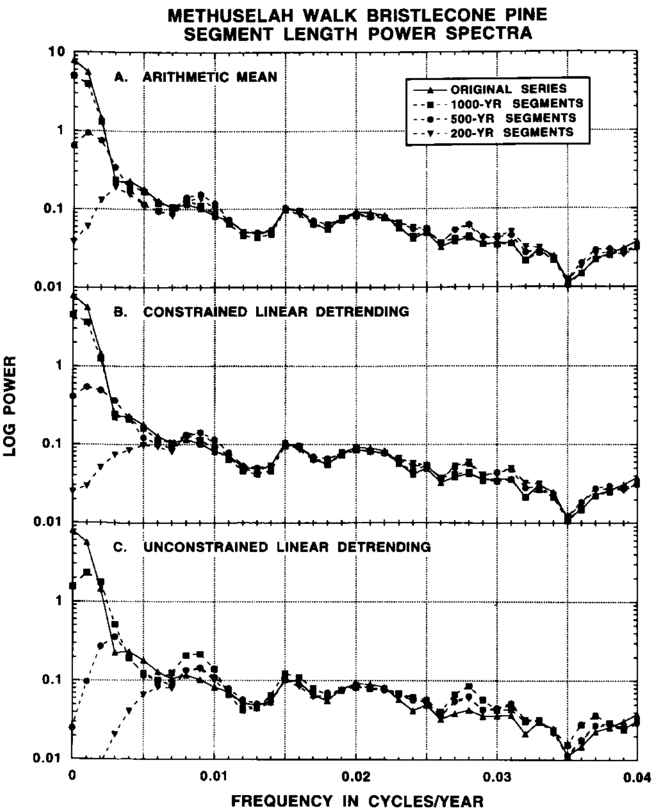

Figure 6 Power spectra of the original series plus the four mean chronologies generated by the different segment lengths and detrending methods. The spectral estimates are only shown over the frequency band 0–0.04 because the higher-frequency estimates are virtually identical. Note the clear loss of low-frequency power in the spectra related to segment length. Also, some additional low-frequency variance in excess of the *l/n* resolvability limit is preserved in the 1000-year segment length case if only the arithmetic mean is removed.

more clearly from the arithmetic mean, with R2 falling from 0.244 to 0.032. Unconstrained linear detrending produced even worse results, with R2 falling from 0.244 to −0.372, a literal sign reversal in the relationship between the original and 200-year segment length low-frequency signals. Although small in amplitude (only 12% of the original low-frequency signal), this artifact clearly indicates the potential danger in overinterpreting low-frequency signals in tree-ring chronologies that exceed the mean segment length used in constructing those series.

Figure 6 shows the power spectra (Jenkins and Watts, 1968) of the unfiltered series generated by the segment length experiments. The spectral estimates are only shown over the frequency range 0–0.04 because the spectra are nearly identical in the higher frequencies. These spectra further confirm the loss of low-frequency variance due to the segment length curse. However, the arithmetic mean method has preserved somewhat more low-frequency variance than the *l/n* resolvability limit should necessarily permit. This is due to the fact that the 'trend in mean' was not actually removed from any of the segments. When all linear trends are removed by unconstrained detrending, the conspicuous decline of low-frequency variance occurs almost precisely where it should for each segment length experiment, i.e., at periods of 1000, 500 and 200 years.

Exorcizing the curse – possibilities

From the results of the previous experiments, the segment length curse is revealed as a serious constraint on the extraction of long-period climatic information from millennia-long tree-ring chronologies. At the very least, great effort should be made to utilize the longest individual tree-ring series available, even if it means some loss of sample size by rejecting shorter series when practical. However, it is also apparent from the experiments using the long bristlecone pine series that the 'trend-in-mean' in raw tree-ring data may, in fact, mean something climatically in certain situations. Therefore, some effort has been made to preserve this information in the development of millennia-long tree-ring chronologies. The simplest approach, used by LaMarche (1974), involves the simple averaging of the raw ring-width measurements.

LaMarche (1974) recognized the inherent limitation of existing tree-ring standardization methods in developing his long Campito Mountain bristlecone pine chronology from living trees and subfossil wood. By carefully selecting wood from overmature trees with 'stripbark' growth forms and by avoiding the rings towards the centres of the stems, he was able to avoid using ring-width series that were likely to be confounded with age-related, nonclimatic growth trends. LaMarche (1974) justified doing this because stripbark trees appear to maintain a relatively constant cambial area through time. In addition, the wood came from trees growing in an open-canopy, upper-treeline environment where the interaction between trees is essentially non-existent. Consequently, he felt justified in simply averaging the retained ring-width series together without using any standardization methods at all. In so doing, he was able to retain all low-frequency variations related to changing mean ring-width, including those potentially exceeding the lengths of the individual ring-width segments.

LaMarche's (1974) mean ring-width chronology is shown in Figure 7, along with another version of the same record obtained by detrending and standardizing the individual segments prior to averaging. The loss of low-frequency variance in the latter record is clearly apparent even though the detrending used was extremely conservative (i.e., negative exponential and linear detrending only). Not only has a large amount of low-frequency variance been removed by standardization, but the temporal history and timing of inferred climatic change is, for some intervals, markedly different. The power spectra of these records (Figure 8) indicates that the majority of the low-frequency variance lost was at wavelengths longer than 700 years. This result is consistent with the 532-year mean segment length of the Campito Mountain ring-width series collection (656 years for the living trees, 452 years for the subfossil wood remnants, and a total range of 69–1460 years). The segment length curse is clearly operative here when the data are detrended and standardized into tree-ring indices.

The additional low-frequency variance preserved in the mean ring-width record has been interpreted by LaMarche (1974) as being principally due to changing summer temperatures. Indeed, this record, especially the outer 1000 years, has been used as a virtual canonical expression of inter-decadal to century-scale temperature variability over large areas of the Northern Hemisphere (e.g., Lamb, 1982). How much of this enhanced low-frequency variability is truly due to changing summer temperatures is unclear. The assumption that stripbark bristlecone pines do not have any age-related growth trends has not been properly tested yet as far as we know. It seems likely that the width of the cambial strip will not stay constant through time and may gradually decrease with increasing age. If so, then a subtle very long-term, nonclimatic trend in ring-width could still be present even in

Downloaded from http://hol.sagepub.com by guest on May 20, 2008
© 1995 SAGE Publications. All rights reserved. Not for commercial use or unauthorized distribution.

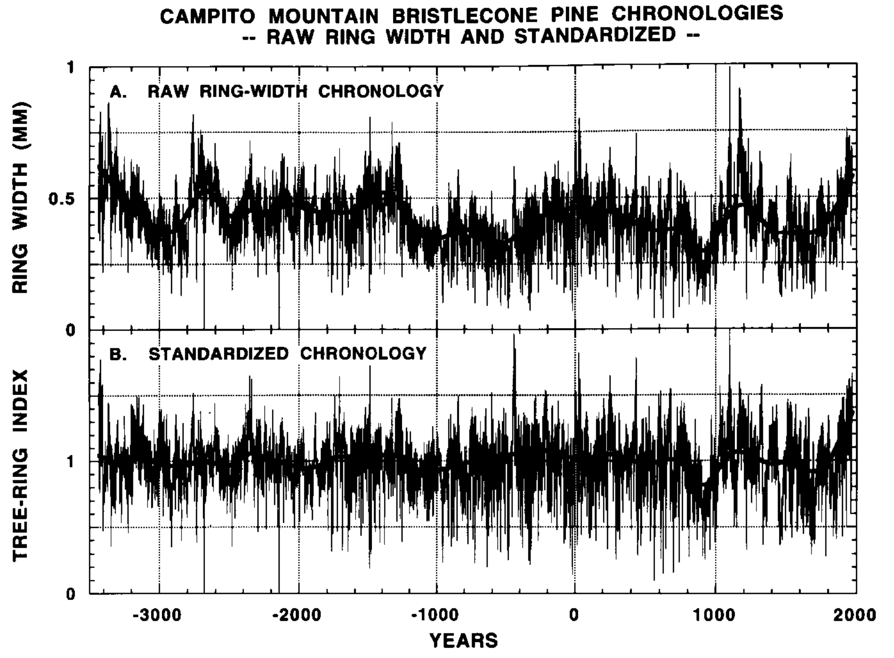

Figure 7 The long Campito Mountain bristlecone pine chronology based on raw ring-widths (A) and standardized tree-ring indices (B). Each may be interpreted in terms of changing summer temperature (e.g., LaMarche, 1974), but standardization has greatly altered the low-frequency signal in the record from that seen in the raw ring-width chronology.

these tree-ring series. This possibility needs to be tested and rejected before the procedure of LaMarche (1974) can be fully accepted.

The LaMarche (1974) method also suffers from its general lack of applicability to most other long-chronology tree-ring data sets. The stripbark growth form is mostly found in very long-lived conifers, especially those growing in xeric habitats. The rarity of the stripbark growth form means that LaMarche's (1974) method cannot be applied to other important subfossil wood collections, like the European oak (*Quercus* sp.) collection (Pilcher *et al.*, 1984) or the Scots pine (*Pinus sylvestris*) collection from Fennoscandia (Briffa *et al.*, 1990; 1992), where the ring-width series are relatively short and biological growth trends are strongly apparent through much of the trees' lives. This indicates the need to find other methods for better preserving the low-frequency information due to climate.

One such alternative method is 'regional curve standardization' (RCS), a term coined by Briffa *et al.* (1992) to describe the use of an empirically defined age/growth function used in

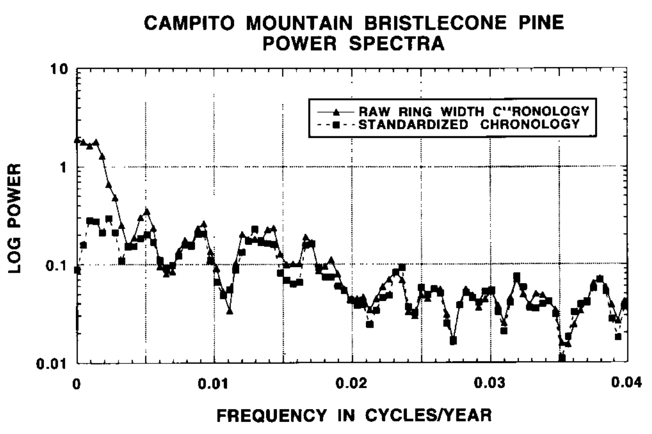

Figure 8 The power spectra of the two Campito Mountain records. Note the decrease in variance in the lowest frequencies in the standardized series (7B). This decrease is almost precisely where it should be if the segment length curse is taken into account. However, it is not clear how much of the additional low-frequency variance in the raw ring-width chronology is truly due to climate variability.

earlier studies (e.g., Mitchell, 1967; see also Becker, 1989 and references in Cook *et al.*, 1990). The premise behind RCS is that there is a single, common age and size-related biological growth curve for a given species and site that can be applied to all series regardless of when the trees were growing. Because this standardization curve is assumed to be an intrinsic, time-invariant feature of tree growth for the species and site under study, RCS allows for the possibility that the overall level of actual tree growth during any particular time period may be systematically over- or underestimated by the regional curve due to changing climatic/environmental conditions. In this sense, RCS allows for long-term changes in the mean due to climate, while at the same time removing trend that is believed to be mostly biological in origin.

The regional curve is estimated empirically by aligning the ring widths not by calendar year but by ring age from the pith. In performing this age-based alignment, the crossdated annual changes in ringwidth between trees due to climate are forced out of alignment and effectively averaged out in the creation of mean regional curve. Even so, the resulting mean-value function is only a coarse estimate of the true regional curve, so a theoretical standardization curve, like the modified negative exponential, is fitted to the series to provide the best estimate of the true regional curve (Figure 9). This final estimate of the regional curve is then used to standardize the individual raw ring-width series in the manner described earlier.

As discussed in Fritts (1976: 279) and noted by Briffa *et al.* (1992), there are several sources of potential error in the RCS procedure. For example, assigning the exact biological age to each ring can be difficult when the series does not begin at the pith. In such cases, either a reasonable guess must be made or the first measured ring is assumed to be the first year of tree growth (Briffa *et al.*, 1992). Either way, the resulting indices will be somewhat biased. However, when the standardized indices are realigned according by calendar year and averaged together, this effect should largely disappear (Briffa *et al.*, 1992). Another, more serious, problem involves the assumption that the estimated regional curve represents the true biological growth curve over long periods of time. While the RCS procedure would seem appropriate for standardizing

Downloaded from http://hol.sagepub.com by guest on May 20, 2008
© 1995 SAGE Publications. All rights reserved. Not for commercial use or unauthorized distribution.

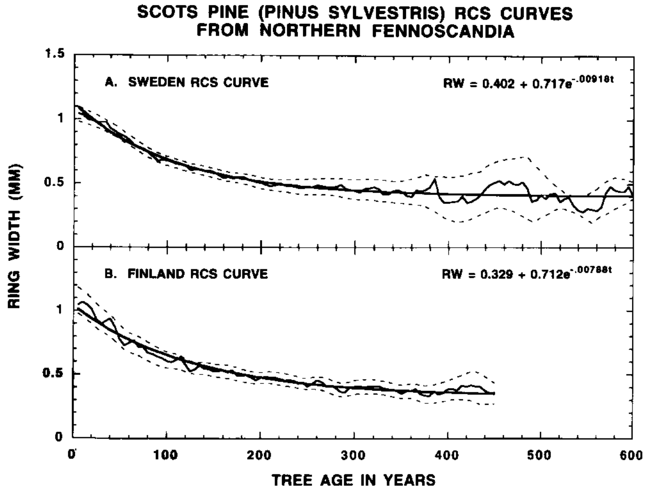

Figure 9 Two examples of RCS curves for *Pinus sylvestris* growing around Lake Torneträsk, northern Sweden (A) and Lake Inari, northern Finland (B). Each curve is based on data for at least several centuries from a number of sites. Note the slight difference in curvature and asymptote, which suggests that variations in regional site characteristics can influence the age/growth relationship. In each case the fitted RCS curve is shown superimposed on the empirically defined relationship, which is bracketed by smoothed one-sigma confidence limits.

ring-width series of trees that grew in the same environment and during the same general time period as the trees used to estimate the regional curve, it is not clear how far back in time this curve will remain reasonably valid. Similarly, if the curve is derived using data spanning a very long period (perhaps many millennia) it is not clear that it is appropriate for all subperiods within this overall time. The regional growth curve could be influenced by the environment in such a way that its form will gradually change over time as climate and site characteristics change. Finally, in practise (e.g., Briffa *et al.*, 1992) RCS series have been found to exhibit lower common variance compared with the same raw data standardized using alternative techniques. This illustrates a general requirement for high series replication to ensure 'acceptable' error variance in the mean value function of RCS series. High replication is practical for recent centuries when numerous living trees may be sampled at will, but it can represent a serious problem during earlier times when sample replication is often fortuitous and largely beyond the control of the dendrochronologist.

Closing remarks

Both LaMarche's (1974) simple method or the more complicated RCS procedure are attempts at breaking the segment length curse. Given that the tree-ring data satisfy the assumptions of either approach, they appear to be reasonable first-order methods. However, neither is sufficiently well developed and tested to represent anything approaching a general solution to this very difficult problem. It may be that such a solution does not exist, or that it exists only as a general umbrella of techniques that are applied according to the origin and characteristics of specific tree-ring data sets. In any case, the segment length curse remains a serious problem that presently limits the recoverable low-frequency climatic variance in millennia-long tree-ring chronologies for paleoclimatic studies.

Acknowledgements

This contribution is dedicated to Don Graybill. It was presented at the Long Tree-Ring Chronology Workshop held in Tucson, Arizona, 1–3 December 1993 and sponsored by the National Science Foundation, Grant ATM 93-14024. Additional work was supported by NSF Grant EAR 93-10093 (Ed Cook) and the EC Environmental Research Programme under EVSV-CT94-0500 (Keith Briffa). Lamont Doherty Contribution No. 5315.

References

Becker, M. 1989: The role of climate on present and past vitality of silver fir forests in the Vosges mountains of northeastern France. *Canadian Journal of Forest Research* 19, 1110–17.

Briffa, K.R., Bartholin, T.S., Eckstein, D., Jones, P.D., Karlén, W., Schweingruber, F.H. and **Zetterberg, P.** 1990: A 1400-year tree-ring record of summer temperatures in Fennoscandia. *Nature* 346, 434–39.

Briffa, K.R., Jones, P.D., Bartholin, T.S., Eckstein, D., Schweingruber, F.H., Karlén, W., Zetterberg, P. and **Eronen, M.** 1992: Fennoscandian summers from AD 500: temperature changes on short and long timescales. *Climate Dynamics* 7, 111–19.

Briffa, K.R., Wigley, T.M.L. and **Jones, P.D.** 1987: Towards an objective approach to standardization. In Kairiukstis, L., Bednarz, Z. and Feliksik, E., editors, *Methods of dendrochronology – 1. Proceedings of the Task Force Meeting of Dendrochronology: East/West Approaches*, Warsaw: IIASA Polish Academy of Sciences, 69–86..

Cook, E.R. 1987: The decomposition of tree-ring series for environmental studies. *Tree-Ring Bulletin* 47, 37–59.

Cook, E.R., Bird, T., Peterson, M., Barbetti, M., Buckley, B., D'Arrigo, R. and **Francey, R.** 1992: Climatic change over the last millennium in Tasmania reconstructed from tree rings. *The Holocene* 2, 205–17.

Cook, E.R., Briffa, K.R., Shiyatov, S. and **Mazepa, V.** 1990: Tree-ring standardization and growth-trend estimation. In Cook, E.R. and Kairiukstis, L.A., editors, *Methods of dendrochronology: applications in the environmental sciences*, Dordrecht: Kluwer/IIASA, 104–23.

Ferguson, C.W. 1969: A 7104-year annual tree-ring chronology for bristlecone pine, *Pinus aristata*, from the White Mountains, California. *Tree-Ring Bulletin* 29, 3–29.

Ferguson, C.W. and **Graybill, D.A.** 1983: Dendrochronology of bristlecone pine: a progress report. In Stuiver, M. and Kra, R.S., editors, International ^{14}C Conference, 11th Proceedings, *Radiocarbon* 25, 287–88.

Fritts, H.C. 1976: Tree rings and climate. London: Academic Press, 567 pp.

Fritts, H.C., Mosimann, J.E. and **Bottorff, C.P.** 1969: A revised computer program for standardizing tree-ring series. *Tree-Ring Bulletin* 29, 15–20.

Granger, C.W. 1966: The typical shape of an economic variable. *Econometrics* 34, 150–61.

Jenkins, G.M. and **Watts, D.G.** 1968: *Spectral analysis and its applications.* San Francisco: Holden-Day, 525 pp.

LaMarche, V.C., Jr 1974: Paleoclimatic inferences from long tree-ring records. *Science* 183, 1043–48.

Lamb, H.H. 1982: *Climate, history and the modern world.* London: Methuen, 387 pp.

Mitchell, V.L. 1967: An investigation of certain aspects of tree growth rates in relation to climate in the central Canadian boreal forest. *University of Wisconsin, Department of Meteorology Technical Report* 33. Task NR 387-022, ONR Contract 1202(07)NSF GP-5572X, Maddison, USA.

Monserud, R.A. 1986: Time series analysis of tree-ring chronologies. *Forest Science* 32, 349–72.

Pilcher, J.R., Baillie, M.G.L., Schmidt, B. and **Becker, B.** 1984: A 7,272-year tree-ring chronology for western Europe. *Nature* 312, 150–52.

Downloaded from http://hol.sagepub.com by guest on May 20, 2008
© 1995 SAGE Publications. All rights reserved. Not for commercial use or unauthorized distribution.